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OF FLUID BETWEEN RIGID CONCENTRIC
SPHERES

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1. Introduction

This preliminary report is concerned with an approximate description of the two dimensional vortical motion in a thin spherical layer of a gravitating, incompressible, inviscid fluid. We suppose that the fluid is contained between an inner rigid ball and an outer rigid concentric sphere and that the fluid, along with the inner spherical surface, has been rotating with constant angular velocity ω about a polar axis until a reference time $t = 0$. Thereafter we suppose that the motion is due to the gravitational attraction of the rotating ball and to the sudden creation at $t = 0$ of concentrated vortices with axis normal to the spheres.

The general objective is to discuss the subsequent motion of these isolated vortices, including the case for which $\omega = 0$. However, in this report we confine the discussion primarily to the motion of a single concentrated vortex in the northern hemisphere when certain equatorial boundary conditions are imposed. The differential equations for the motion of such a vortex appear below; and they are followed by an approximate description of its geometric path for a period of time of such duration that it is not necessary to use a computer for the numerical integration of the equations.

There are many physical phenomena which are related to the motion of vortices in a rotating fluid; and the analysis of this kind of motion poses various inherently interesting mathematical problems. Here, the investigation was undertaken with the hope

that the results could be used to approximate roughly the path of a hurricane generated in the northern hemisphere.

2. Formulation

Let a and $a+h$ be the radii of two rigid concentric spheres which contain a spherical layer of fluid. Suppose that $h > 0$ is small compared with a ; and that the inner sphere rotates about its polar axis with constant angular velocity ω . Let the motion of the fluid be referred to the inner sphere. Let ρ denote the distance of a fluid particle from the center of the sphere while ϕ and θ respectively denote its longitude and colatitude. In terms of these coordinates the velocity of a particle relative to the inner rotating sphere is defined by the components

$$u = (\rho \sin \theta) \frac{d\phi}{dt} = \text{tangential component toward the east;}$$

$$v = -\rho \frac{d\theta}{dt} = \text{tangential component toward the north;}$$

$$w = \frac{d\rho}{dt} = \text{radial component.}$$

If the only body force acting is that due to the gravitational attraction of the solid ball defined by the inner sphere, then the basic hydrodynamical equations which define the motion of the fluid are the continuity equation

$$\frac{1}{\rho} \frac{\partial \rho^2 w}{\partial \rho} + \frac{1}{\sin \theta} \left[\frac{\partial u}{\partial \phi} - \frac{\partial (v \sin \theta)}{\partial \theta} \right] = 0$$

and the momentum equations

$$\frac{du}{dt} - \frac{uv \cot \theta}{\rho} + \frac{uw}{\rho} + 2\omega w \sin \theta - 2\omega v \cos \theta = - \frac{1}{\delta_0 \rho \sin \theta} \frac{\partial p}{\partial \phi} ;$$

$$\frac{dv}{dt} + \frac{vw}{\rho} + \frac{u^2 \cot \theta}{\rho} + 2\omega u \cos \theta = \frac{1}{\delta_0 \rho} \frac{\partial p}{\partial \theta} ;$$

$$\frac{dw}{dt} - \frac{v^2}{\rho} - \frac{u^2}{\rho} - 2\omega u \sin \theta = -g - \frac{1}{\delta_0} \frac{\partial p}{\partial \rho} .$$

In these equations the differential operator with respect to the time means

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{u}{\rho \sin \theta} \frac{\partial}{\partial \phi} - \frac{v}{\rho} \frac{\partial}{\partial \theta} + w \frac{\partial}{\partial \rho} .$$

The symbol δ_0 denotes the constant density of the fluid; p denotes the pressure; and $g\rho$ denotes the gravitational potential modified by the centrifugal effect of rotation.

Since h is small compared with the large radius a of the inner sphere; and since

$$w(\phi, \theta, a+h, t) = w(\phi, \theta, a, t) = 0$$

let us assume that the radial velocity and the radial variation of u and v can be neglected. Let us also assume that the motion is such that the nonlinear terms in the tangential momentum equations can be neglected; and that the radial momentum equation can be replaced with the hydrostatic law

$$p(\phi, \theta, \rho, t) = p(\phi, \theta, a, t) - g\delta_0(\rho-a) .$$

Under these assumptions which characterize the linear shallow water theory; and with the notation

$$\tilde{u}(\phi, \theta, t) = u(\phi, \theta, a, t) ,$$

$$\tilde{v}(\phi, \theta, t) = v(\phi, \theta, a, t) ,$$

$$\tilde{p}(\phi, \theta, t) = p(\phi, \theta, a, t) ;$$

an approximation to the motion is determined by the equations

$$(2.1) \quad \frac{\partial \tilde{u}}{\partial \phi} - \frac{\partial(\tilde{v} \sin \theta)}{\partial \theta} = 0 ;$$

$$(2.2) \quad \frac{\partial \tilde{u}}{\partial t} - 2\omega \tilde{v} \cos \theta = - \frac{1}{\delta_0 a \sin \theta} \frac{\partial \tilde{p}}{\partial \phi} ;$$

$$(2.3) \quad \frac{\partial \tilde{v}}{\partial t} + 2\omega \tilde{u} \cos \theta = \frac{1}{\delta_0 a} \frac{\partial \tilde{p}}{\partial \theta} .$$

The elimination of \tilde{p} from (2.2) and (2.3) and the use of (2.1) leads to the equation

$$(2.4) \quad \frac{\partial}{\partial t} \frac{1}{a \sin \theta} \left[\frac{\partial(\tilde{u} \sin \theta)}{\partial \theta} + \frac{\partial \tilde{v}}{\partial \phi} \right] + \frac{2\omega \tilde{v} \sin \theta}{a} = 0 .$$

It should be remarked that the quantity

$$\tilde{\zeta} = \frac{1}{a \sin \theta} \left[\frac{\partial(\tilde{u} \sin \theta)}{\partial \theta} + \frac{\partial \tilde{v}}{\partial \phi} \right]$$

is the radial component of vorticity when radial variations are neglected. An integration of (2.4) yields

$$(2.5) \quad \frac{1}{a \sin \theta} \left[\frac{\partial \tilde{u} \sin \theta}{\partial \theta} + \frac{\partial \tilde{v}}{\partial \phi} \right] + \frac{2\omega}{a} \int_0^t \tilde{v} \sin \theta \, d\tau = \tilde{\zeta}(\phi, \theta, 0)$$

where $\tilde{\zeta}(\phi, \theta, 0)$ represents the vorticity prevalent in the fluid layer at time $t = 0$.

The equations (2.1) and (2.5) are the basic ones for the motion under consideration. They can be studied by introducing the function $\tilde{\psi}(\phi, \theta, t)$ and setting

$$(2.6) \quad (a \sin \theta) \frac{d\phi}{dt} = \tilde{u} = \frac{1}{a} \frac{\partial \tilde{\psi}}{\partial \theta} ,$$

$$(2.7) \quad -a \frac{d\theta}{dt} = \tilde{v} = \frac{1}{a \sin \theta} \frac{\partial \tilde{\psi}}{\partial \phi} ;$$

in this way (2.1) is automatically satisfied. Then if we substitute (2.6) and (2.7) in (2.5) we find $\tilde{\psi}$ must satisfy

$$(2.8) \quad \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left[(\sin \theta) \frac{\partial \tilde{\psi}}{\partial \theta} \right] + \frac{1}{\sin^2 \theta} \frac{\partial^2 \tilde{\psi}}{\partial \phi^2} + 2\omega \int_0^t \frac{\partial \tilde{\psi}}{\partial \phi} d\tau = a^2 \tilde{\zeta}(\phi, \theta, 0) .$$

The problem now is to find a function $\tilde{\psi}$ which satisfies certain prescribed conditions along the boundary of a domain \tilde{D} on the reference sphere; and satisfies (2.8) at each point of \tilde{D} . Before we consider this problem, however, let us discuss briefly the simpler case in which the spheres are fixed and the contained spherical layer of fluid is motionless until $t = 0$.

3. The Case of no Rotation

If $\omega = 0$ the equation (2.8) becomes

$$(3.1) \quad \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} (\sin \theta) \frac{\partial \tilde{\psi}}{\partial \theta} + \frac{1}{\sin^2 \theta} \frac{\partial^2 \tilde{\psi}}{\partial \phi^2} = a^2 \tilde{\zeta}(\phi, \theta, 0) .$$

It is interesting to observe that if we use the transformation, (see Fig. 1),

$$z = r e^{i\phi} = (a \tan \frac{\theta}{2}) e^{i\phi} = x + iy ,$$

then (3.1) can be reduced to the ordinary two dimensional potential equation. For example, suppose we wish to analyze the motion of a concentrated vortex in the zonal layer defined by

$$D : \quad \begin{cases} \alpha < \theta < \beta \\ 0 \leq \phi \leq 2\pi \end{cases}$$

on the reference sphere subject to the requirement that along the boundary the normal velocity v must be zero along $\theta = \alpha$ and $\theta = \beta$. If we use the above transformation the problem can be reduced to solving

$$(3.2) \quad \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = \mu \delta(x - x_1) \delta(y - y_1)$$

for the annular domain

$$D : \quad \begin{cases} q_1 = a \tan \frac{\alpha}{2} < r < a \tan \frac{\beta}{2} = q_2 \\ 0 \leq \phi \leq 2\pi \end{cases}$$

with the boundary conditions

$$\psi(q_1, \phi) = \psi(q_2, \phi) = 0 .$$

In equation (3.2) μ represents the strength of the vortex; δ stands for the Dirac delta function; and x_1, y_1 correspond to the position of the vortex on the sphere.

It should be remarked that the annular domain D is a stereographic projection of the zone \tilde{D} as Fig. 1 indicates.

The above observations suggest the possibility of developing a general theory for the motion of concentrated vortices on a fixed sphere. In the course of doing this the author found that it is basically analogous to the Helmholtz-Kirchoff theory for the planar motion of rectilinear vortices.

4. Fundamental Solution. Concentrated Vortex on a Rotating Sphere

Let us return now to the equation (2.8) which can be written in the form

$$(4.1) \quad \begin{aligned} \sigma\psi &\equiv \frac{1}{\sin\theta} \frac{\partial}{\partial\theta} (\sin\theta) \frac{\partial\tilde{\psi}}{\partial\theta} + \frac{1}{\sin^2\theta} \frac{\partial^2\tilde{\psi}}{\partial\phi^2} \\ &= a^2\tilde{\zeta}(\phi, \theta, 0) - 2\omega \int_0^t \frac{\partial\tilde{\psi}}{\partial\phi} d\tau . \end{aligned}$$

This equation can be analyzed in several different ways. One way is to introduce an appropriate Green's function and then present the partial differential equation as an integral equation. The Neumann expansion of the integral equation leads to

$$\tilde{\psi}(\phi, \theta, t) = \tilde{\psi}_0(\phi, \theta) + \sum_{n=1}^{\infty} \frac{(\omega t)^n}{n!} \tilde{\psi}_n(\phi, \theta) .$$

It can be shown that the function in this expansion must satisfy

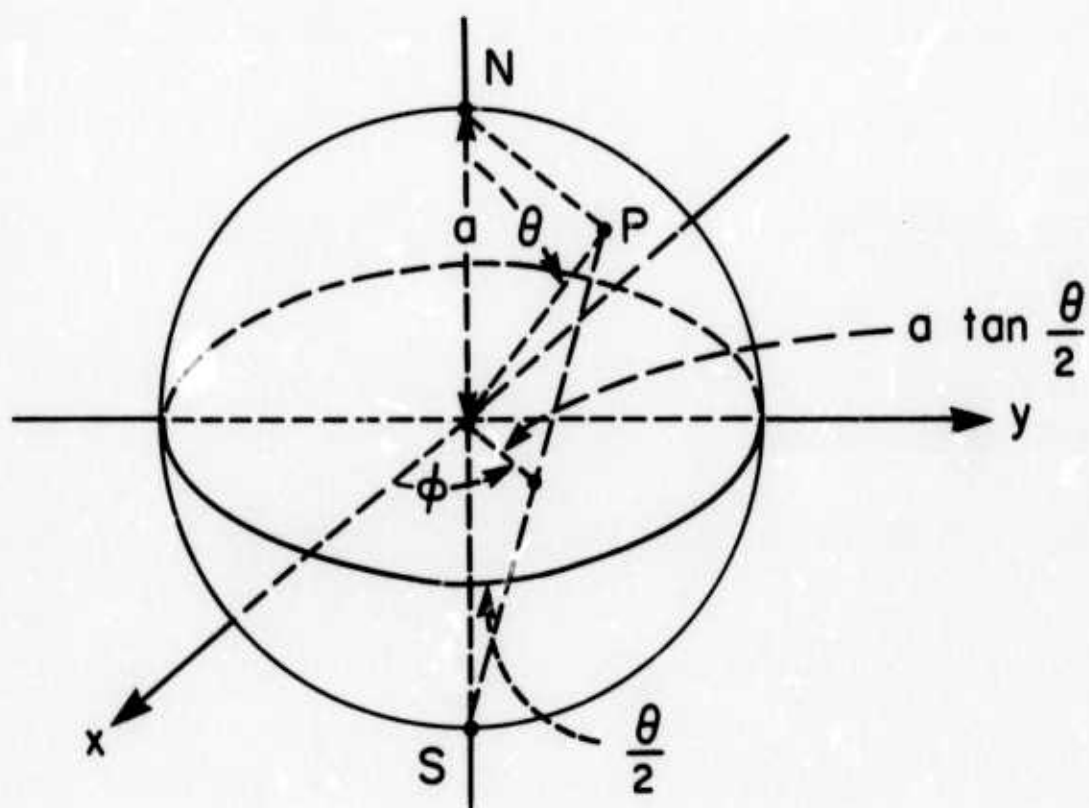


Figure 1

$$\sigma \tilde{\psi}_0 = a^2 \tilde{\zeta}(\phi, \theta, 0) ,$$

$$\sigma \tilde{\psi}_n = -2 \frac{\partial}{\partial \phi} \tilde{\psi}_{n-1} ;$$

and therefore, by virtue of the transformation

$$z = (a \tan \frac{\theta}{2}) e^{i\phi} ,$$

they can be determined by solving a sequence of ordinary potential problems.

Another way to solve (4.1) is to use transform theory based on finite Fourier transforms in conjunction with Legendre transforms. This way seems most convenient for our immediate aim which is to find the function $\tilde{\psi}$ associated with the creation at $t = 0$ of a vortex of strength μ concentrated at (ϕ_1, θ_1) where

$$0 < \theta_1 < \pi .$$

In other words, our first object is to solve

$$(4.2) \quad \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} (\sin \theta) \frac{\partial G}{\partial \theta} + \frac{1}{\sin^2 \theta} \frac{\partial^2 G}{\partial \phi^2} + 2\omega \int_0^t \frac{\partial G}{\partial \phi} d\tau = \frac{\mu \delta(\phi - \phi_1) \delta(\theta - \theta_1)}{\sin \theta_1}$$

for

$$0 \leq \theta < \pi , \quad 0 \leq \phi \leq 2\pi ;$$

that is, for the whole sphere excluding the south pole where $Q(\phi, \theta, t)$ may be singular.

Let us assume that the behavior of G at the south pole is such that

$$L_{\theta \rightarrow \pi} \sin \theta G(\phi, \theta, t) = 0 ,$$

$$L_{\theta \rightarrow \pi} \sin \theta \frac{\partial G}{\partial \theta} = \text{const.}$$

Under these assumptions it is known that G can be expressed in the form

$$(4.3) \quad G(\phi, \theta, t) = A(\theta, t) + \frac{1}{2\pi} \sum_{n=1}^{\infty} (2n+1) \sum_{m=1}^n \frac{(n-m)!}{(n+m)!} \begin{bmatrix} A_{nm}(t) \cos m\phi \\ + B_{nm}(t) \sin m\phi \end{bmatrix} P_n^m(\cos \theta)$$

where the coefficients are the transforms

$$A(\theta, t) = \int_0^{2\pi} G(\alpha, \theta, t) d\alpha ;$$

$$A_{nm}(t) = \int_0^{2\pi} \int_0^{\pi} G(\alpha, \beta, t) \cos m\alpha P_n^m(\cos \beta) \sin \beta d\beta d\alpha ;$$

$$B_{nm}(t) = \int_0^{2\pi} \int_0^{\pi} G(\alpha, \beta, t) \sin m\alpha P_n^m(\cos \beta) \sin \beta d\beta d\alpha .$$

The function $P_n^m(\cos \theta)$ is the associated Legendre spherical harmonic of degree n and order m . It can be defined by

$$P_n^m(\cos \theta) = \begin{cases} (-1)^m (\sin \theta)^m \left(\frac{d}{d \cos \theta} \right)^m P_n(\cos \theta) , & m \leq n \\ 0 , & m > n \end{cases}$$

and it satisfies

$$\begin{aligned} & \frac{1}{\sin \theta} \frac{d}{d\theta} (\sin \theta) \frac{d}{d\theta} P_n^m(\cos \theta) \\ & + \left[n(n+1) - \frac{m^2}{\sin^2 \theta} \right] P_n^m(\cos \theta) = 0 . \end{aligned}$$

Notice that no previous condition on G is affected if we change G by a constant.

The transform $A(\theta, t)$ must be continuous at $\theta = \theta_1$ and satisfy

$$\frac{\partial}{\partial \theta} (\sin \theta) \frac{\partial A}{\partial \theta} = \mu \delta(\theta - \theta_1) .$$

Since $A(\theta, t)$ must be bounded at $\theta = 0$, the solution of the last equation, excepting an additive constant, is uniquely given by

$$(4.4) \quad A(\theta) = \begin{cases} \mu \ln \tan \frac{\theta_1}{2} , & \theta \leq \theta_1 , \\ \mu \ln \tan \frac{\theta}{2} , & \theta_1 \leq \theta . \end{cases}$$

This function can be expanded in the form

$$(4.5) \quad A(\theta) = -\frac{\mu}{2\pi} \ln \cos \frac{\theta_1}{2} + \frac{\mu}{2\pi} \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} [(-1)^n - P_n(\cos \theta_1)] P_n(\cos \theta)$$

where $P_n(\quad) = P_n^0(\quad)$.

The transforms $A_{nm}(t)$ and $B_{nm}(t)$ must satisfy

$$-n(n+1)A_{nm}(t) + 2\omega m \int_0^t B_{nm}(\tau) d\tau = \mu \cos m\phi_1 \cdot P_n^m(\cos \theta_1) ,$$

$$-n(n+1)B_{nm}(t) - 2\omega m \int_0^t A_{nm}(\tau) d\tau = \mu \sin m\phi_1 \cdot P_n^m(\cos \theta_1)$$

and these yield

$$(4.6) \quad \begin{aligned} A_{nm}(t) &= - \frac{\mu P_n^m(\cos \theta_1)}{n(n+1)} \cos m \left[\phi_1 - \frac{2\omega t}{n(n+1)} \right], \\ B_{nm}(t) &= - \frac{\mu P_n^m(\cos \theta_1)}{n(n+1)} \sin m \left[\phi_1 - \frac{2\omega t}{n(n+1)} \right]. \end{aligned}$$

The substitution of these transforms in (4.3) gives

$$(4.7) \quad \begin{aligned} G(\phi, \theta, t) &= A(\theta) \\ &- \frac{\mu}{2\pi} \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} \sum_{m=1}^n \frac{(n-m)!}{(n+m)!} P_n^m(\cos \theta_1) P_n^m(\cos \theta) \\ &\quad \cdot \cos m \left[\phi - \phi_1 + \frac{2\omega t}{n(n+1)} \right]. \end{aligned}$$

Next, the addition theorem

$$(4.8) \quad \begin{aligned} P_n[\cos \theta \cos \theta_1 + \sin \theta \sin \theta_1 \cos \lambda] \\ &= P_n(\cos \theta) P_n(\cos \theta_1) \\ &\quad + 2 \sum_{m=1}^n \frac{(n-m)!}{(n+m)!} P_n^m(\cos \theta_1) P_n^m(\cos \theta) \cos m\lambda \end{aligned}$$

shows that we can write

$$A(\theta)$$

$$(4.9) \quad G(\phi, \theta, t) = -\frac{\mu}{4\pi} \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} \left\{ \begin{array}{l} P_n \left[\begin{array}{l} \cos \theta \cos \theta_1 \\ + \sin \theta \sin \theta_1 \cos(\phi - \phi_1 + \frac{2\omega t}{n(n+1)}) \end{array} \right] \\ - P_n(\cos \theta_1) P_n(\cos \theta) \end{array} \right\}.$$

Hence, from (4.5), we see that $G(\phi, \theta, t)$ can be exhibited in the form

$$(4.10) \quad G(\phi, \theta, t) = -\frac{\mu}{4\pi} \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} \left\{ \begin{array}{l} P_n \left[\begin{array}{l} \cos \theta \cos \theta_1 \\ + \sin \theta \sin \theta_1 \cos(\phi - \phi_1 + \frac{2\omega t}{n(n+1)}) \end{array} \right] \\ - (-1)^n P_n(\cos \theta) \end{array} \right\}.$$

Finally, by using

$$(4.11) \quad -\sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} (-1)^n P_n(x) = 1 + \ln \frac{(1+x)}{2}$$

we find that

$$(4.12) \quad G(\phi, \theta, t) = -\frac{\mu}{2\pi} \left[\frac{1}{2} + \ln \cos \frac{\theta_1}{2} + \ln \cos \frac{\theta}{2} \right] - \frac{\mu}{4\pi} \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} P_n \left[\begin{array}{l} \cos \theta \cos \theta_1 \\ + \sin \theta \sin \theta_1 \cos(\phi - \phi_1 + \frac{2\omega t}{n(n+1)}) \end{array} \right].$$

The reason for retaining the constant $\frac{1}{2} + \ln \cos \frac{\theta_1}{2}$ is that when we do

$$G(\phi, \theta, t) = G(\phi, \theta, t; \phi_1, \theta_1)$$

is symmetric in θ and θ_1 .

Except for (ϕ_1, θ_1) and the south pole, the velocity components are given by

$$\tilde{u} = \frac{1}{a} \frac{\partial G}{\partial \theta} ; \quad \tilde{v} = \frac{1}{a \sin \theta} \frac{\partial G}{\partial \phi} .$$

The velocity field in the neighborhood of the concentrated vortex can be estimated by studying the first term of the expansion of $G(\phi, \theta, t)$ in powers of ωt , namely

$$\begin{aligned} (4.13) \quad G_0(\phi, \theta, t) &= -\frac{\mu}{4\pi} \left[1 + 2 \ln \cos \frac{\theta_1}{2} + 2 \ln \cos \frac{\theta}{2} \right] \\ &\quad - \frac{\mu}{4\pi} \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} P_n \left[\begin{array}{c} \cos \theta \cos \theta_1 \\ + \sin \theta \sin \theta_1 \cos(\phi - \phi_1) \end{array} \right] \\ &= \frac{\mu}{4\pi} \left\{ \begin{array}{l} -1 - \ln \cos^2 \frac{\theta_1}{2} - \ln \cos^2 \frac{\theta}{2} \\ + 1 + \ln \left[\frac{1 - \cos \theta \cos \theta_1 - \sin \theta \sin \theta_1 \cos(\phi - \phi_1)}{2} \right] \end{array} \right\} \\ &= \frac{\mu}{4\pi} \ln \left[\tan^2 \frac{\theta}{2} + \tan^2 \frac{\theta_1}{2} - 2 \tan \frac{\theta}{2} \tan \frac{\theta_1}{2} \cos(\phi - \phi_1) \right] . \end{aligned}$$

This gives the dominant part of the velocity of a point near (ϕ_1, θ_1) . It corresponds to the case of no rotation; and if we transform to the z -plane introduced above via

$$z = a \tan \frac{\theta}{2} e^{i\phi}$$

we have

$$(4.14) \quad G_0 = \frac{\mu}{4\pi} \ln(z - z_1)(\bar{z} - \bar{z}_1) - \frac{\mu}{4\pi} \ln a^2$$

$$= \frac{\mu}{2\pi} \operatorname{Re} \ln(\bar{z} - \bar{z}_1) - \frac{\mu}{2\pi} \ln a$$

where z_1 is the image of (ϕ_1, θ_1) and $\operatorname{Re} F(z)$ denotes the real part of $F(z)$. The velocity components determined by G_0 can be calculated from

$$\tilde{u}_0 = \frac{1}{a} \frac{\partial G_0}{\partial \theta} = \frac{\mu(a^2 + z\bar{z})}{4\pi a^2 \sqrt{z\bar{z}}} \operatorname{Re} \frac{z}{z - z_1} ;$$

$$\tilde{v}_0 = \frac{1}{a \sin \theta} \frac{\partial G_0}{\partial \phi} = \frac{\mu(a^2 + z\bar{z})}{4\pi a^2 \sqrt{z\bar{z}}} \operatorname{Re} \frac{iz}{z - z_1} .$$

These show that as $z \rightarrow z_1$ the velocity approaches infinity; but the component in the direction from z to z_1 is zero. Therefore in the neighborhood of (ϕ_1, θ_1) the fluid rotates about the vortex point with velocity of the order of $\frac{1}{|z - z_1|}$. From this, it can be deduced that the velocity field defined by G in the neighborhood of (ϕ_1, θ_1) behaves qualitatively in the same way as the field defined by G_0 . In other words, the concentrated vortex at (ϕ_1, θ_1) has no tendency to move — it is not self propelling.

Notice that if the vortex is at the north pole, i.e.,

$\theta_1 = 0$, then

$$G(\phi, \theta, t; \phi_1, 0) = -\frac{\mu}{2\pi} \left[\frac{1}{2} + \ln \cos \frac{\theta}{2} \right]$$

$$- \frac{\mu}{4\pi} \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} P_n(\cos \theta)$$

$$G(\phi, \theta, t; \phi_1, 0) = G_0(\phi, \theta, t; \phi_1, 0) \\ = \frac{\mu}{2\pi} \ln \tan \frac{\theta}{2} .$$

This function is such that

$$L_{\theta \rightarrow 0} \sin \theta G_\theta(\phi, \theta, t; \phi_1, 0) = \frac{1\mu}{2\pi} .$$

5. Concentrated Vortex in Northern Hemisphere. Either Velocity Component Zero at the Equator

We proceed to find the stream function for a concentrated vortex traveling in the northern hemisphere and subject to the condition that the normal velocity of the fluid at the equator is zero. The boundary condition then is

$$\tilde{v}(\phi, \frac{\pi}{2}, t) = \frac{1}{a \sin \theta} \tilde{\psi}_\phi(\phi, \frac{\pi}{2}, t) = 0$$

or

$$\tilde{\psi}(\phi, \frac{\pi}{2}, t) = c(t) .$$

However, we know that nothing is lost if we impose

$$\tilde{\psi}(\phi, \frac{\pi}{2}, t) = 0 .$$

The stream function for this case can be formed from $G(\phi, \theta, t; \phi_1, \theta_1)$ if we assume that the principle of reflection across the equator will lead toward the desired result. In fact, it is easy to verify that

$$(5.1) \quad \psi = G(\phi, \theta, t; \phi_1, \theta_1) - G(\phi, \theta, t; \phi_1, \pi - \theta_1)$$

is the desired function. We refrain from a discussion of the velocity field defined by (5.1) in favor of the next case in which the eastward velocity

$$\tilde{u} = \frac{1}{a} \frac{\partial \tilde{\psi}}{\partial \theta}$$

is prescribed at the equator.

We turn to the problem of finding ψ such that with the boundary condition

$$\frac{1}{a} \cdot \psi_{\theta}(\phi, \frac{\pi}{2}, t) = c = \text{const.}$$

the equation

$$(5.2) \quad \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} (\sin \theta) \frac{\partial \psi}{\partial \theta} + \frac{1}{\sin^2 \theta} \frac{\partial^2 \psi}{\partial \phi^2} + 2\omega \int_0^t \frac{\partial \psi}{\partial \tau} d\tau = \frac{\mu \delta(\phi - \phi_1) \delta(\theta - \theta_1)}{\sin \theta_1}$$

is satisfied for

$$0 \leq \phi \leq 2\pi, \quad 0 \leq \theta < \frac{\pi}{2}.$$

If we assume that

$$(5.3) \quad \lim_{\theta \rightarrow 0} \sin \theta \psi_{\theta} = \frac{\mu_0}{2\pi}$$

an integration of (5.2) over the northern hemisphere yields

$$(5.4) \quad \int_0^{2\pi} \psi_{\theta}(\phi, \frac{\pi}{2}, t) d\phi = \mu + \mu_0.$$

This shows that the prescription of $\psi_{\theta}(\phi, \frac{\pi}{2}, t)$ must satisfy the compatibility condition (5.4). If we wish to satisfy

$$\psi_{\theta}(\phi, \frac{\pi}{2}, t) = ac$$

then we must have

$$\mu_0 = 2\pi ac - \mu .$$

As we have seen, the condition (5.3) is satisfied by

$$\frac{\mu_0}{\mu} G(\phi, \theta, t; \phi_1, 0) = \frac{\mu_0}{2\pi} \ln \tan \frac{\theta}{2} .$$

Consider the function

$$(5.5) \quad \psi(\phi, \theta, t) = \frac{\mu_0}{2\pi} \ln \tan \frac{\theta}{2} + G(\phi, \theta, t; \phi_1, \theta_1) + G(\phi, \theta, t; \phi_1, \pi - \theta_1) .$$

A short computation shows that

$$\psi_{\theta}(\phi, \frac{\pi}{2}, t) = \frac{\mu_0}{2\pi} + \frac{\mu}{2\pi} .$$

Hence (5.5) satisfies the boundary condition that the eastward velocity at the equator is constant and equal to c if

$$\mu_0 = 2\pi ac - \mu .$$

We have now shown that

$$(5.6) \quad \psi(\phi, \theta, t) = \frac{(2\pi ac - \mu)}{2\pi} \ln \tan \frac{\theta}{2} + G(\phi, \theta, t; \phi_1, \theta_1) + G(\phi, \theta, t; \phi_1, \pi - \theta_1)$$

is the desired stream function.

Let us turn our attention to a study of the path of the vortex at $[\phi_1(t), \theta_1(t)]$. As in the basic Helmholtz theory for

the motion of interacting concentrated vortices, the velocity of the vortex at $[\phi_1(t), \theta_1(t)]$ is equal to the field velocity determined at $[\phi_1, \theta_1]$ by all of the other vortices. That is, the equations for the motion of the vortex are

$$\dot{\phi}_1 = \frac{1}{a^2 \sin \theta_1} \frac{\partial}{\partial \theta} \left[\frac{(2\pi ac - \mu)}{2\pi} \ln \tan \frac{\theta}{2} \right] \Bigg|_{\substack{\phi=\phi_1 \\ \theta=\theta_1}} + G(\phi, \theta, t; \phi_1, \pi - \theta_1) \Bigg|_{\substack{\phi=\phi_1 \\ \theta=\theta_1}}$$

and

$$\dot{\theta}_1 = - \frac{1}{a^2 \sin \theta_1} \frac{\partial}{\partial \phi} \left[G(\phi, \theta, t; \phi_1, \pi - \theta_1) \right] \Bigg|_{\substack{\phi=\phi_1 \\ \theta=\theta_1}}.$$

In expanded form these are

$$(5.7) \quad \dot{\phi}_1 = \frac{d\phi_1}{dt} = \frac{(2\pi ac - \mu)}{2\pi a^2 \sin^2 \theta_1} + \frac{\mu}{8\pi a^2 \cos^2 \frac{\theta_1}{2}} - \frac{\mu \cos \theta_1}{4\pi a^2} \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} P'_n \left[\begin{array}{c} -\cos^2 \theta_1 \\ +\sin^2 \theta_1 \cos \frac{2\omega t}{n(n+1)} \end{array} \right] \cdot \left[1 + \cos \frac{2\omega t}{n(n+1)} \right];$$

and

$$(5.8) \quad \dot{\theta}_1 = \frac{d\theta_1}{dt} = - \frac{\mu \sin \theta_1}{4\pi a^2} \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} P'_n \left[\begin{array}{c} -\cos^2 \theta_1 \\ +\sin^2 \theta_1 \cos \frac{2\omega t}{n(n+1)} \end{array} \right] \cdot \sin \frac{2\omega t}{n(n+1)}.$$

It seems that numerical integration is necessary in order to trace the path of the vortex for moderately large or large values of ωt . Our intention is to pursue this in a later report; however, as a preliminary step, we can assume that ωt is so small that a sufficiently good approximation to the path can be found by expanding $\dot{\phi}_1$ and $\dot{\theta}_1$ in powers of ωt and retaining those of degree no higher than the second. In addition let us suppose hereafter that $c = 0$.

If each term in (5.7) and (5.8) is expanded in powers of ωt ; and if we retain powers no higher than the second we find

$$(5.9) \quad \dot{\phi}_1 = -\frac{\mu}{2\pi a^2 \sin^2 \theta_1} + \frac{\mu}{8\pi a^2 \cos^2 \frac{\theta_1}{2}} - \frac{\mu \cos \theta_1}{2\pi a^2} \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} \left\{ \begin{array}{l} P'_n(-\cos 2\theta_1) \\ -\frac{(\omega t)^2}{n^2(n+1)^2} \left[\begin{array}{l} P'_n(-\cos 2\theta_1) \\ +2 \sin^2 \theta_1 \cdot P''_n(-\cos 2\theta_1) \end{array} \right] \end{array} \right\}$$

and

$$(5.10) \quad \dot{\theta}_1 = -\frac{\mu(\omega t) \sin \theta_1}{2\pi a^2} \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} P'_n(-\cos 2\theta_1) .$$

The series which appear in the last equations can be summed and they lead to

$$(5.11) \quad \dot{\phi}_1 = -\frac{\mu}{4\pi a^2 (1 - \cos \theta_1) \cos \theta_1} - \frac{\mu(\omega t)^2}{\pi a^2 \cos \theta_1} \int_0^{\cos \theta_1} \frac{\lambda^3 \ln \lambda}{1 - \lambda^2} d\lambda ;$$

$$(5.12) \quad \dot{\theta}_1 = \frac{\mu \omega t \ln \cos \theta_1}{2\pi a^2 \sqrt{1 - \cos^2 \theta_1}}.$$

In order to express $\dot{\phi}_1$ and $\dot{\theta}_1$ in powers of t explicitly we need to expand $\cos \theta_1$ in powers of t and insert the expansion in (5.11) and (5.12). If we do this and retain only powers of t less than the third we find

$$(5.13) \quad \dot{\phi}_1 = -\frac{\mu}{\pi a^2 \cos \theta_0} \left\{ \frac{1}{8 \sin^2 \frac{\theta_0}{2}} + (\omega t)^2 \left[\int_0^{\cos \theta_0} \frac{\lambda^3 \ln \lambda}{1 - \lambda^2} d\lambda + \frac{\mu(1 - 2 \cos \theta_0) \ln \cos \theta_0}{8\pi a^2 \omega \sin^4 \frac{\theta_0}{2} \cos \theta_0} \right] \right\}$$

$$(5.14) \quad \dot{\theta}_1 = \frac{\mu \omega t \ln \cos \theta_0}{2\pi a^2 \sin \theta_0}$$

where θ_0 is the colatitude of the initial position of the vortex.

The approximate equations (5.13) and (5.14) show the following if μ , the strength of the vortex, is positive; and θ_0 is greater than $\pi/3$. When ωt is very small the vortex moves along a path which is almost parabolic. Since $-a\dot{\theta}_1$ is the velocity to the north, equation (5.14) shows that the rate of change of latitude is zero at $t = 0$ and the latitude increases as t increases. Equation (5.13) shows that the vortex starts with a westward motion but after a while the positive term

$$- \frac{\mu(\omega t)^2}{\pi a^2 \cos \theta_0} \left[\int_0^{\cos \theta_0} \frac{\lambda^3 \ln \lambda}{1 - \lambda^2} d\lambda + \frac{\mu(1 - 2 \cos \theta_0) \ln \cos \theta_0}{8\pi a^2 \omega \sin^4 \frac{\theta_0}{2} \cos \theta_0} \right]$$

becomes dominant and the vortex then moves to the east. The following figure shows a qualitative sketch of the path.

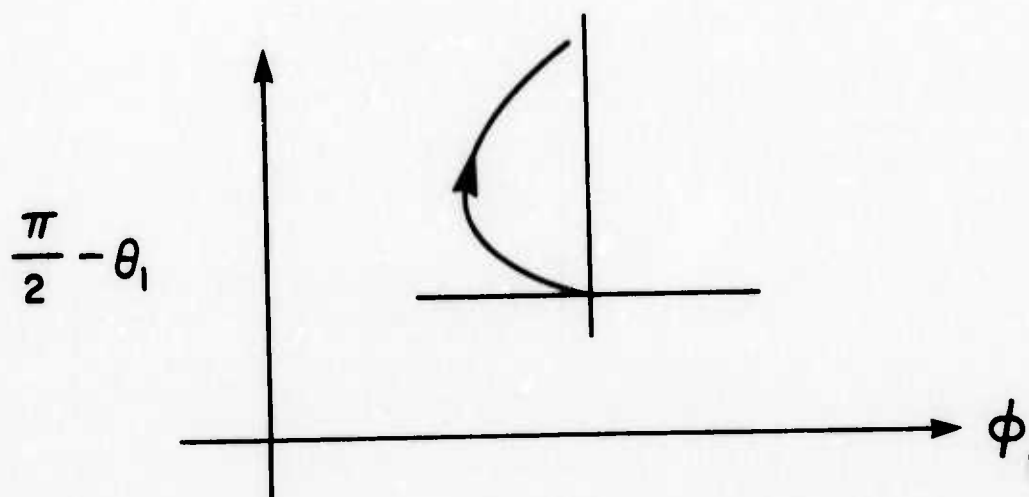


Figure 2

This sketch exhibits some of the characteristics of the observed paths of hurricanes generated in the Caribbean sea or some other southern part of the North Atlantic ocean.